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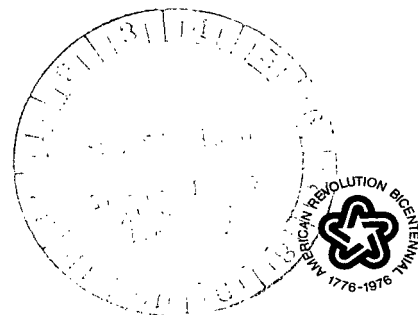
VELOCITY SURVEYS IN A TURBINE STATOR ANNULAR-CASCADE FACILITY USING LASER DOPPLER TECHNIQUES

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16. Abstract

A laser Doppler velocimeter (LDV) was used to determine the flow conditions downstream of an annular cascade operating at an exit critical velocity ratio of 0.87. Two modes of LDV operation (continuous scan and discrete point) were investigated. Conventional pressure probe measurements were also made for comparison with the LDV results. Biasing errors that occur in the LDV measurement of velocity components were also studied. In addition, the effect of pressure probe blockage on the flow conditions was determined with the LDV.

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FACILITY USING LASER DOPPLER TECHNIQUES

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SUMMARY

A laser Doppler velocimeter (LDV) was used to experimentally determine the velocity and flow angle downstream of an annular cascade of stator vanes. The vanes were tested near the design, mean-radius, critical velocity ratio of 0.87. Two modes (discrete point and continuous scan) of LDV operation were investigated. In the discrete point mode, data were obtained at a fixed number of points in the flow field. In the continuous scan mode, data were obtained by continuously traversing the test section at fixed radial positions. A conventional pressure probe was also used to obtain the velocity and flow angle for comparison with the LDV measurements. Biasing errors that occur in the LDV measurement of velocity components were also investigated. The effect of pressure probe blockage on the velocity level downstream of the vanes was also determined with the LDV.

The velocity obtained with the LDV and that obtained with the pressure probe usually agreed within 1 percent. Wall static pressures measured without the probe blocking the flow were used (assuming a linear variation with radius) to calculate the velocity from the total pressure probe measurements. The agreement in the flow angle was, generally, within 1^O near the mean radius, but differences of 2^O to 3° were found near the end walls. The two modes (discrete point and continuous scan) of obtaining LDV data agreed, generally, within 1 percent. The time required for the continuous scan mode of operation was about one-fifth that needed for the discrete point mode. In the vane wakes, biasing errors of about 3 percent were found in the LDV measurements of velocity components $\pm45^O$ to the flow direction. No significant biasing errors were noted in the free-stream measurements or in the wake measurements $\pm20^O$ to the flow direction. The pressure probe blockage was found to decrease the velocity level in the test region significantly. This was in agreement with the wall static pressure increases observed in previous tests. On humid days, water vapor condensation was observed in the cascade. The LDV measurements obtained under these conditions are considered unreliable because of the possibility that the large condensation particles do not adequately track the flow.

INTRODUCTION

Aerodynamic measurements obtained in high subsonic flows can be influenced by conventional immersion instrumentation. For example, the significant effect of pressure probe blockage on the static pressure distribution in annular turbine stator cascades has been reported in references 1 and 2. In advanced engine designs, where the stator may operate in the transonic regime, the problem is especially severe. A laser Doppler velocimeter (LDV) offers one promising method of obtaining flow velocities and direction without disturbing the flow field. This has resulted in a program being conducted, at the NASA Lewis Research Center, for the purpose of developing an LDV system capable of measuring the velocity and flow angle downstream of an annular cascade of stator vanes.

Preliminary results of this study have been reported in reference 3. A number of problems associated with the LDV system were noted during these tests. First, the time required to obtain a set of LDV measurements at discrete points in the flow field was felt to be too long. Typically, 1 hour was required to take a circumferential survey (30 points) at a given radial position. Second, the LDV system of reference 3 permitted only the measurement of the axial and tangential velocity components. Because the axial component was much smaller than the tangential component, the accuracy of the axial component was considered to be less than for the tangential component. A check on the calculated velocity magnitude was, therefore, felt to be desirable and could be accomplished if the velocity along the calculated flow direction could be measured.

Modifications to the LDV system were, therefore, made to alleviate these problems. Specifically, to decrease the time required to obtain LDV measurements, a continuous scan mode of operation (analogous to that used successfully for pressure probes) was incorporated into the LDV system. Measurement of the velocity component, along any direction, was accomplished by using a rotatable Dove prism. Tests of the modified LDV system were then performed in the annular cascade facility described in reference 1.

In this report, a description of the modified LDV system and the results obtained are presented. Tests were made near the design value of the mean-radius critical velocity ratio, which was 0.87 for these vanes. The two modes of obtaining LDV measurements (continuous scan and discrete point) are compared with each other and with the results obtained with conventional pressure probes. Biasing errors in the measurement of velocity components in the vane wakes were observed and investigated.

The effect of pressure probe blockage on the flow conditions downstream of the vanes was also determined with the LDV. In addition, measurement problems caused by water vapor condensation were observed and are discussed.

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APPARATUS AND PROCEDURE

Cascade Facility

The full-annular cascade and a cross-sectional view of the facility are shown in figures 1 and 2, respectively. The cascade facility consists primarily of an inlet bellmouth, blading, and an exhaust section. The bellmouth was designed to accelerate the flow to uniform axial conditions at the vane inlet. The blading consists of a full-annular ring of 72 vanes. A sector of vanes, located in the test section, is shown in figure 3. These vanes had been damaged (during prior hot engine tests) and were repaired with an epoxy filler, which was smoothed and faired to the vane surface. Because the LDV and pressure probe measurements were made with the same set of vanes, the damage should not affect the comparison.

The twisted vanes have a height of 9.78 centimeters and, at the mean radius, an axial chord and solidity of 5.08 centimeters and 1.64, respectively. The vane tip diameter is 81.03 centimeters.

Laser Doppler Velocimeter

The original version of this laser Doppler velocimeter (LDV) system, developed for measuring the flow velocity and direction downstream of an annular cascade of stator vanes, has been described in reference 3. In this section, a general description of the modified LDV system is presented. A more detailed discussion is given in reference 4.

Theory. - The modified LDV system used for this investigation is shown in figure 4 and a schematic representation is given in figure 5. The LDV system is of the dual scatter type described in reference 5. This type of system has, as a general feature, two beams of equal intensity focused at a single point in the flow. At the intersection of the two beams (referred to as the probe volume), constructive and destructive interference of the light waves occurs, forming an interference fringe pattern. As particles entrained in the fluid pass through these fringes, they alternately scatter and do not scatter light. Some of this fluctuating scattered light is then collected by a photomultiplier tube whose output is modulated at the rate at which the scattering particles cross the fringe pattern. Measurement of this rate, called the Doppler frequency, allows the particle velocity normal to the fringes to be calculated. This explanation of the dual scatter system is often referred to as the fringe model and was first described in reference 6.

The two mode-matching lenses, shown in figure 5, fix the diameter of the probe volume (125 μm) and ensure that the two beams cross at their minimum diameters,

thereby providing uniform fringe spacing. The Dove prism allows the two beams to be rotated without altering the beam intersection point. This modification from the original system (ref. 3) allows the fringe pattern orientation to be varied, permitting the measurement of the velocity component along any direction in the axial-tangential plane. The window (fig. 6) through which the beams pass was made of 0.318-centimeter-thick Plexiglass acrylic plastic bent to conform to the cascade surface. Also shown in figure 6 is the modified window used for the probe blockage tests. The pinhole (350-μm diam) placed in front of the photomultiplier tube (fig. 5) reduces the amount of unwanted light that can reach the tube. In addition, it reduces the effective length of the probe volume to about 0.8 millimeter.

The laser and all the optics were mounted on a single plate (figs. 4 and 5) that rested on two other plates. The top plate could move only in the radial direction (about 13 cm), and the second plate was constrained to move in a circular arc (about 8°) about the cascade axis. Thus, the position of the beam intersection could be varied. The bottom stationary plate was supported by a rigid structure bolted to the test cell floor (fig. 1). A wooden cover was placed over the laser and optics to protect the system and to contain the laser light.

Seeding. - A necessary requirement for the LDV is a sufficiently large concentration of scattering particles in the fluid to achieve a reasonable data rate. Furthermore, the size of these particles must be such that they accurately track the flow. A detailed study of the particle tracking problem, for this cascade, has been made under a NASA grant (ref. 7). For the region where the LDV measurements were made in this investigation (1.27 cm downstream of the vane trailing edge), it was found that the particles should have a diameter of 1.0 micrometer or less. This ensured that the differences between the velocity magnitudes and directions of a particle and the fluid would be less than 0.5 percent and 1°, respectively.

To meet these requirements, a commercially available particle seeding generator was used in this investigation. The generator consisted of an atomizer followed by a separator that removed large droplets. A silicone oil was used to provide the seeding particles. The generator specifications indicated that the droplets produced were to have a mean diameter of 0.6 micrometer and a standard deviation of 0.3 micrometer. No direct measurement of the particle size was made.

The aerosol was injected into the mainstream at the bellmouth inlet upstream of the test region (fig. 2). The injection nozzle was mounted on the laser protective cover and consisted of five ports that dispersed the aerosol over an area of about 50 square centimeters. The position of the injection nozzle could be controlled so that part of the aerosol would pass through the fringe pattern at all measurement points in the test region.

Electronic and data processing. - A block diagram of the electronic system used to measure the Doppler frequency is shown in figure 7(a). The form of a typical output signal from the photomultiplier tube is shown (waveform 1) in figure 7(b). This sinus-

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oidal type of signal results from a single seeding particle alternately scattering and not scattering light as it passes through the fringe pattern. After amplification, the signal passes through a high-pass filter to remove the low-frequency component (pedestal) and through a low-pass filter to reduce the noise. The filtered signal (waveform 2 in fig. 7(b)) is then processed by the LDV signal processor that is described in reference 4. To be considered a valid signal, the filtered waveform must have at least 10 consecutive cycles with an amplitude greater than a preset threshold, which was determined by the noise level (see waveform 2). For valid signals, the output from the LDV signal processor is a single-cycle square wave with a period t (all symbols defined in the appendix) equal to eight periods of the Doppler frequency f_D (waveform 3 in fig. 7(b)).

The period of the square wave was measured by using a commercial computing counter with an accuracy of 1 nanosecond. This results in an accuracy of the calculated velocity (for this investigation) of about 0.5 percent. A programmer was used to control the computing counter and to process the data. Two separate data handling procedures (i.e., discrete point and continuous scan) were used in this investigation and will now be described.

The discrete point method consists of taking LDV data at a fixed number (about 30) of circumferential points at a given radial position. At each point, data were obtained at two fringe pattern orientations that gave velocity components at approximately $\pm 20^{\circ}$ from the expected flow direction. This was done to prevent errors in the measurements, as discussed in the section Biasing Errors in Turbulent Flows. The velocity component V_j is calculated from the Doppler frequency f_D and the fringe spacing s by the following relations (ref. 5):

$$V_j = V \cos(\alpha - \varphi_j) = f_D s = \frac{8}{t} s \qquad j = 1, 2 \tag{1}$$

$$s = \frac{\lambda}{2 \sin\left(\frac{\theta}{2}\right)} \tag{2}$$

The wavelength of the laser light λ was 0.5145 micrometer, and the beam crossing angle θ was measured to be $4.68 \pm 0.02^{\circ}$. This results in a fringe spacing s of 6.30 ± 0.03 micrometers. For each component, the mean velocity component $\overline{V_j}$ and standard deviation σ were calculated for a preset number (usually 1000) of individual measurements. Occasional bad measurements (i.e., caused by large particles lagging the flow) were disregarded by the procedure described in reference 4. Referring to figure 8, the velocity $\overline{V}$ and flow angle $\overline{\alpha}$ are calculated from the components $\overline{V}_1$ and $\overline{V}_2$ by

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$$\overline{\alpha} = \tan^{-1}\left(\frac{\overline{V}_1 \cos \varphi_2 - \overline{V}_2 \cos \varphi_1}{\overline{V}_2 \sin \varphi_1 - \overline{V}_1 \sin \varphi_2}\right) \tag{3}$$

$$\overline{V} = \frac{\overline{V}_1}{\cos(\overline{\alpha} - \varphi_1)} \tag{4}$$

A check on the computed velocity magnitude $\overline{V}$ was then made by taking an additional set of measurements in the computed flow direction $\overline{\alpha}$. Because 1 hour was typically needed to complete a circumferential survey of 30 points by this procedure, the faster continuous scan method was developed.

The continuous scan method consists of calculating a running average of the velocity as the test region is continuously traversed in the circumferential direction at a fixed radial position. In this mode of operation, a survey could be completed in about 4 minutes; the time being determined by the speed of the circumferential drive motor. The programmer was used to compute the running average velocity $\overline{V}_i$ by using the computation algorithm for a first-order, low-pass, digital filter (ref. 8)

$$\overline{V}_i = P\overline{V}_{i-1} + (1 - P)V_i \qquad i = 1, 2, \ldots, n \tag{5}$$

where V_i is the ith velocity measurement, $\overline{V}_i$ is the running mean velocity after i measurements, and P is a number between 0 and 1 and is similar to an analog filter time constant. The choice of P depends on both the data rate and the scan rate, with the object being adequate filtering without the loss of sensitivity to changes in mean velocity. The value of P used in this investigation was 0.9 and was determined during initial testing. Individual bad velocity measurements were eliminated by disregarding those values that differed from the current mean velocity by more than a preset fraction (i.e., 0.4) of the current mean velocity. The computed mean velocity was plotted as a function of circumferential position on an X-Y recorder. The standard deviation is not obtained in the continuous scan method.

For the continuous scan mode, the fringe pattern orientation was set so that the velocity magnitude would be measured directly. To do this, the flow angle $\overline{\alpha}$ must, of course, be known. For these tests, an average flow angle obtained from the discrete point measurements was used at each radial position. Small changes that occur in the flow angle with circumferential position do not significantly affect the velocity magnitude. For example, differences as large as 5° between the fringe pattern orientation and the true flow angle result in an error in the velocity magnitude of less than 0.4 percent. If the flow angle is not known or changes more drastically, a procedure similar to that used in the discrete point method could be used. That is, continuous scan surveys of

the velocity components on either side of the estimated flow direction could be taken.

Biasing errors. - Although the LDV is capable of accurately measuring the velocity of individual particles, significant errors in statistical quantities can arise when the flow is fluctuating. Even if the particles are uniformly distributed in the fluid, a biasing occurs because the amount of fluid (and particles) passing through the probe volume (fringe pattern) is proportional to the fluid velocity. Therefore, for those velocities greater than the mean, more particles pass through the probe volume, resulting in more samples (measurements) being taken at the higher velocities. This type of biasing has been described in reference 9, where it was shown that the error in the mean velocity is approximately equal to the square of the turbulence intensity. For example, at a turbulence intensity of 10 percent, the calculated mean velocity will be about 1 percent greater than the true value.

In addition to this biasing, if the velocity is obtained from the measurement of two velocity components, major errors due to angle biasing can occur. Essentially, angle biasing is caused by fluctuations in the flow direction. This occurs because the data rate (rate of velocity measurements) depends on the flow angle. For example, if the flow direction is parallel to the fringes (fig. 9), no measurements are obtained (zero data rate) because the particles do not cross any fringes. The maximum data rate is obtained when the flow direction is normal to the fringes since the maximum number of fringes will be intersected. The important point to note is that for velocity component measurements the data rate changes if the flow angle fluctuates; the data rate being larger for fluctuations that are more normal to the fringe pattern. A simple example will help to clarify the situation.

Referring to figure 9, consider a simple flow that is fluctuating between only two flow conditions (V_1 and V_2), each having the same velocity but different flow angles. As explained previously, the flow condition more normal to the fringe pattern (i. e., V_1) will have a higher data rate. Therefore, more measurements (for a given time interval) will be obtained for the larger velocity component ($V_{x, 1}$) than for the smaller velocity component ($V_{x, 2}$). This angle fluctuation will then result in the velocity component measurement being biased high. A detailed analysis of this phenomenon has been described in reference 4. It was found that the biasing error is dependent on the turbulence intensity (no biasing for zero turbulence), the number of fringes, the particle size distribution, and the angle between the mean flow direction and the component measurement (error increases as this angle increases).

Survey Probe

The vane exit flow conditions were also determined with a calibrated combination probe. The probe, shown in figure 10, was capable of measuring total pressure, total

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temperature, static pressure, and flow angle. The position of the probe was fixed at an angle of 64° (from the axial direction), which corresponds to the design flow angle at the mean radius. Continuous scan surveys were taken with the probe, at the same axial location and for the same vanes as were used for the laser tests. The probe actuator drive mechanism completely covered the LDV window area, so that survey probe and LDV measurements could not be made concurrently.

The probe tip was made of stainless-steel tubing with an outside diameter of 0.102 centimeter and a wall thickness of 0.018 centimeter. The total pressure was obtained from a total head tube with an inside bevel of 30°, which reduces the sensitivity of the measurement to flow angle misalinement. The flow angle was determined from the measured pressure difference of two 45°-angled tubes and prior calibration. The probe total temperature and static pressure measurements, as will be explained subsequently, were not used for this investigation.

Because the total temperature remains constant through the cascade, it was more convenient and reliable to measure the total temperature at the bellmouth inlet. The probe static pressure was not used since it reflects the effect of probe blockage. For comparison with the laser measurements, what is desired is the static pressure that exists when the probe is not present. This static pressure was estimated by assuming a linear distribution with radius. The hub and tip wall static pressures used for the estimation were determined when the probe was not blocking the flow. It was also assumed that the probe blockage does not change the total pressure distribution. The velocity is then calculated from

$$V = \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right)RT' \left[1 - \left(\frac{p}{p'}\right)^{(\gamma-1)/\gamma}\right]} \tag{6}$$

where

$$p = p_h + (p_t - p_h)\left(\frac{r - r_h}{r_t - r_h}\right) \tag{7}$$

Because the velocity depends on the total temperature (eq. (6)) and probe surveys and LDV measurements were made at different times, the critical velocity ratio V/V_{cr} was used for comparison purposes. The critical velocity ratio is independent of total temperature and is given by

$$\frac{V}{V_{cr}} = \sqrt{\left(\frac{\gamma + 1}{\gamma - 1}\right)\left[1 - \left(\frac{p}{p'}\right)^{(\gamma-1)/\gamma}\right]} \tag{8}$$

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All pressures were measured with calibrated strain-gage pressure transducers. The total temperature was measured with four copper-constantan thermocouples located 90° apart circumferentially at the bellmouth inlet.

Procedure

In operation, atmospheric air from the test cell was drawn through the cascade and exhausted into the laboratory altitude exhaust system. Test conditions in the cascade were set by controlling the pressure ratio across the blade row with two different-size throttle valves located in the exhaust system. Static taps located downstream of the test section, where the flow was considered to be circumferentially uniform, were used to set this pressure ratio. Both the laser and survey probe test conditions were set in this manner. The probe blockage did not noticeably affect these downstream static pressures. All tests were conducted at a pressure ratio that corresponded to the design value of the critical velocity at the mean radius, which was 0.87.

RESULTS AND DISCUSSION

Comparison of Laser and Survey Probe Measurements

The velocity (expressed as critical velocity ratio) obtained with the laser Doppler velocimeter (LDV) and that obtained with the survey probe are compared in figure 11. In general, the agreement is good, with most of the data agreeing within 1 percent. However, at a radial position of 9 percent of span from the hub, the agreement in the free-stream region (i.e., circumferential positions about 5° to 7.5°) is not good. Two things can be noted at this radial position. First, the LDV measurements indicate that the free streams of adjacent vane passages are at slightly different velocity (and consequently different static pressure) levels. For the survey pressure probe calculations, the static pressure was obtained, as discussed previously, by a linear estimation between the hub and tip wall values obtained when the probe was not blocking the flow. This procedure results, as shown in figure 11, in a constant free-stream velocity level. Probe static pressure measurements, which were not used in this study because they were affected by probe blockage, did however indicate that the static pressures of the two adjacent vane passages were slightly different. The static taps on the walls, however, were not detailed enough to make a better estimate than the constant value used. It is, therefore, felt that the LDV measurements in this region reflect the true flow conditions better than do the survey probe values. Second, the two vane wakes are significantly different. This may be due to the damage and subsequent repairs made to these

vanes, which are discussed in the section Cascade Facility.

The flow angles obtained with the LDV and the survey probe are compared in figure 12. At a radial position of 52 percent of span from the hub, the agreement is good, usually within 1^O. However, differences of about 2^O to 3° are noted in the wake regions at radial positions of 9 and 93 percent of span from the hub. This may be due to the more severe radial velocity gradients that occur near the walls and the possibility that the LDV and survey probe measurements were obtained at slightly different radial positions.

Comparison of Laser Modes of Operation

Figure 13 compares the measurements made in the discrete point and continuous scan modes of LDV operation. The data for each mode were taken on different days for a number of reasons (e. g. , time requirements and programmer changes). For the continuous scan mode, the data (shown by a solid line in the figure) represent the mean value of velocity obtained from the X-Y plots. The agreement between the two LDV modes of operation is very good, with most of the data agreeing within 1 percent.

As discussed previously, 1 hour was typically needed for a discrete point survey of 30 individual points. A single continuous scan required about 4 minutes. However, three separate scans, or 12 minutes, would be necessary to duplicate the data obtained in the discrete point mode (i. e. , two velocity components and a check on the velocity magnitude). Therefore, the continuous scan mode of LDV operation takes about one-fifth the time required for the discrete point mode of operation.

Biasing Errors in Turbulent Flows

In addition to the velocity and flow direction measurements, the LDV is also capable of providing information on the turbulent structure of the flow (ref. 10). Although turbulence measurements were not the intent of this investigation, they are reported herein since it was found that the angle biasing errors were related to the turbulence intensity. Figure 14 shows the measured turbulence intensity as a function of circumferential and radial position. The turbulence is assumed to be isotropic, and the turbulence intensity is then equal to the standard deviation σ of the velocity measurements divided by the mean velocity $\overline{V}$. In the free-stream regions, the turbulence intensity is about 2. 5 percent and agrees well with the value found in similar cascade tests (ref. 11). As expected, the intensities are much higher in the wake regions, reaching values up to 10 percent.

The angle biasing of the velocity component measurements is shown in figure 15 for

values obtained at a radial position of 52 percent from the hub. Velocity component measurements were obtained at two points: one in the free stream and one in the wake region, where the turbulence intensities were approximately 2.5 and 7.5 percent, respectively. At each of these points, velocity components $\overline{V}_j$ were measured over a range of angles from the mean flow direction $\overline{\alpha}$, which was about 64° from the axial direction. The velocity measurement in the flow direction $\overline{V}$ is assumed to be correct and is used as a basis of comparison for the velocity component measurements. That is, at any measurement angle $\overline{\alpha} - \varphi_j$, the velocity component should be $\overline{V} \cos(\overline{\alpha} - \varphi_j)$ and any difference between this calculated value and the measured value $\overline{V}_j$ is considered a biasing error.

In the free stream very little error occurs in component measurements over the range of angles covered (fig. 15). However, in the vane wake, where the turbulence intensity is higher, large errors can result. For example, component measurements $\pm45^{O}$ to the flow direction (i.e., φ_j of 19° and 109°) have biasing errors of about 3 percent. And in the axial direction ($\varphi_j = 0^{O}$) the error is over 35 percent. Axial and tangential velocity component measurements were used in reference 3. It is, therefore, estimated that the values reported therein can be in error (in the wake regions) by about 8 percent (high) in the calculated velocity $\overline{V}$ and 8° (low) in the flow angle $\overline{\alpha}$. For this investigation, all component measurements (excluding fig. 15) were made at about $\pm20^{O}$ from the flow direction, where no significant biasing errors occurred. Also shown in figure 15, by the dashed lines, are the biasing errors calculated by the theoretical method given in reference 4. Qualitative agreement is noted between the theoretical and experimental results.

Effect of Survey Probe Blockage on Flow

The effect of the survey probe on the wall static pressure distribution downstream of the vanes, for this cascade, has been given in reference 1. It was found that the probe blockage tends to increase the static pressures in comparison to the values obtained with the probe removed. The increased static pressure with probe blockage indicates that the local flow velocity level must have decreased.

To confirm these results, the LDV was also used to study the effect of probe blockage, since a direct measurement of velocity is possible. The results are shown in figure 16. For the probe blockage tests, the laser window was modified (fig. 6) so that the probe could be extended into the flow. The blockage results, shown by the dashed lines in the figure, are for the probe at a fixed radial position of 9 percent of span from the hub. Also shown in figure 16 is the projection of the probe stem to the survey plane at the measured flow angles. For the unobstructed flow the original window (fig. 6) was used, and the results are shown by the solid line. Both tests were conducted at the

same ratio of downstream static pressure to inlet total pressure that was used to set the cascade test conditions. The LDV measurements show a significant decrease in velocity due to the survey probe blockage. This is in agreement with the static pressure rise found previously (refs. 1 and 12).

Effect of Water Vapor Condensation on Laser Measurements

On humid days, water vapor in the air was observed to condense on expanding through the stator. This can be seen from figures 17 and 18, which show continuous scan LDV surveys on days when condensation did and did not occur, respectively. At radial positions of 9 and 52 percent of span from the hub, condensation was present and the signal is seen to be noisier than the traces without condensation. Because of the large size of the condensation particles and the possibility that they do not track the flow adequately, these LDV measurements are considered unreliable. Condensation was not observed at a radial position of 93 percent of span from the hub. This is due, possibly, to the lower velocity level at this radial position. In fact, condensation could be prevented at radial positions of 9 and 52 percent of span from the hub by decreasing the velocity level by about 10 percent.

CONCLUDING REMARKS

Two modes (discrete point and continuous scan) of obtaining laser Doppler velocimeter (LDV) measurements were found to agree well with each other and with the results obtained by using a conventional pressure probe. The time required for the continuous scan mode of operation was about one-fifth that needed for the discrete point mode. However, quantitative information on the turbulence intensity level is not available for the continuous scan mode. Also the time requirements for the discrete point mode could possibly be decreased by automatic sequential data handling techniques. Therefore, no recommendation can be made as to which LDV mode of operation should be used for a particular application.

Biasing errors that may occur in the LDV measurement of velocity components were observed and circumvented by measuring the velocity components at no more than $\pm 20^{\circ}$ to the flow direction. Biasing errors of this type can be a serious problem and must be carefully considered whenever making LDV measurements in highly turbulent environments.

Pressure probe blockage tests were performed and were found to significantly decrease the local velocity level. These tests were performed at high subsonic flow conditions, but the effect is expected to be more severe for transonic flow and for low-

aspect-ratio blading. Under these conditions, the LDV may be the only method capable of obtaining useful information.

SUMMARY OF RESULTS

A laser Doppler velocimeter (LDV) was used to experimentally determine the velocity and flow angle downstream of an annular cascade of stator vanes. The vanes were tested near the design, mean-radius, critical velocity ratio of 0.87. Two modes (discrete point and continuous scan) of LDV operation were investigated. In the discrete point mode, data were obtained at a fixed number of points in the flow field. In the continuous scan mode, data were obtained by continuously traversing the test section at fixed radial positions. A conventional pressure probe was also used to obtain the flow conditions for comparison with the LDV measurements. Biasing errors that occur in the LDV measurement of velocity components were investigated. The effect of pressure probe blockage on the flow conditions downstream of the vanes was also determined with the LDV. The results of the investigation are summarized as follows:

1. The agreement between the velocities obtained with the LDV and the pressure probe was usually within 1 percent. The agreement in the flow angle was, generally, within 1^O near the mean radius, but differences of 2^O to 3° were found near the end walls.

2. The two modes (discrete point and continuous scan) of obtaining LDV data agreed, generally, within 1 percent. The time required for the continuous scan mode of operation was about one-fifth that needed for the discrete point mode.

3. In the vane wakes, biasing errors of about 3 percent were found in the LDV measurement of velocity components $\pm45^O$ to the flow direction. No significant biasing errors were noted in the free-stream measurements or in the wake measurements $\pm20^O$ to the flow direction.

4. The pressure probe blockage decreased the velocity level in the test region significantly. This was in agreement with the wall static pressure increases observed in previous tests.

5. On humid days, water vapor condensation was observed in the cascade. The LDV measurements obtained under these conditions are considered unreliable because of the possibility that the large condensation particles do not adequately track the flow.

Lewis Research Center,
    National Aeronautics and Space Administration,
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            505-04.

APPENDIX - SYMBOLS

f_D Doppler frequency, Hz

n   number of measurements

P   number between 0 and 1, eq. (5)

p   pressure, N/m^2

R   gas constant, J/kg-K

r   radial position, m

s   fringe spacing, m

T   temperature, K

t   period, sec

V   velocity, m/sec

V_j velocity component, m/sec

α flow angle measured from axial direction, deg

γ ratio of specific heats

θ laser beam crossing angle, deg

λ laser wavelength, m

σ standard deviation, $\sqrt{\dfrac{\sum\limits_{n}(V_i - \overline{V})^2}{n-1}}$, m/sec

φ_j angle of velocity component V_j with respect to axial direction, deg

Subscripts:

cr   flow conditions at Mach 1

h   hub

i i^{th} measurement

t   tip

Superscripts:

$-$ mean value

'   total-state condition

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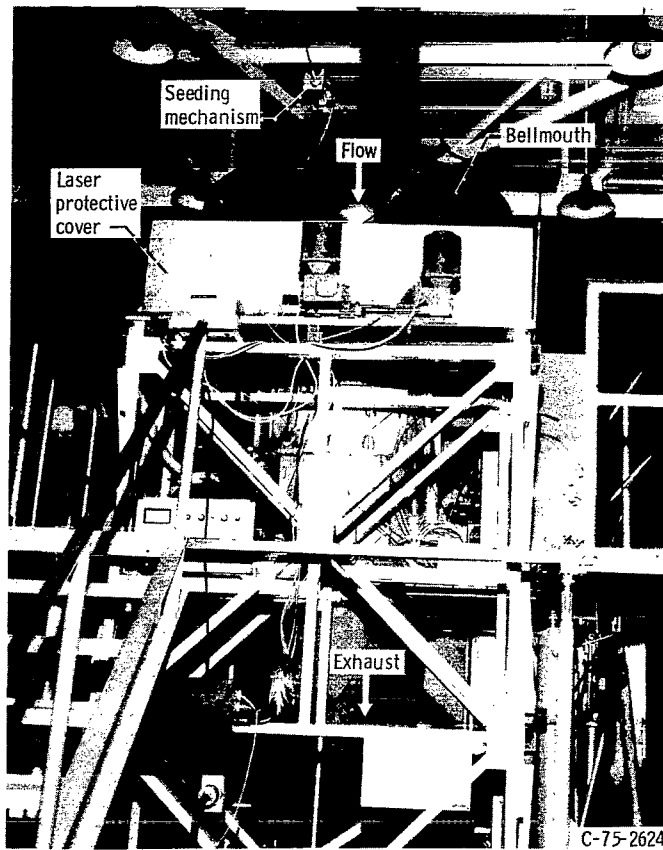
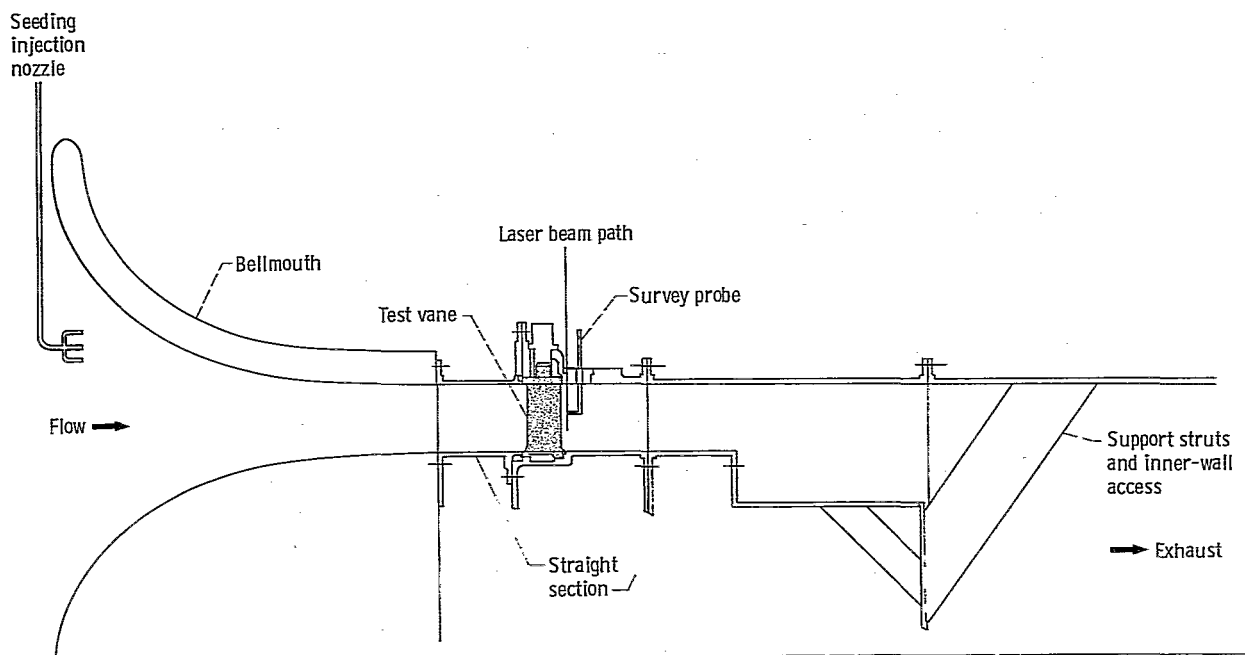Figure 1. - 81-Centimeter-diameter full-annular cascade facility.

Figure 2. – Schematic cross-sectional view of 81-centimeter-diameter full-annular cascade facility.
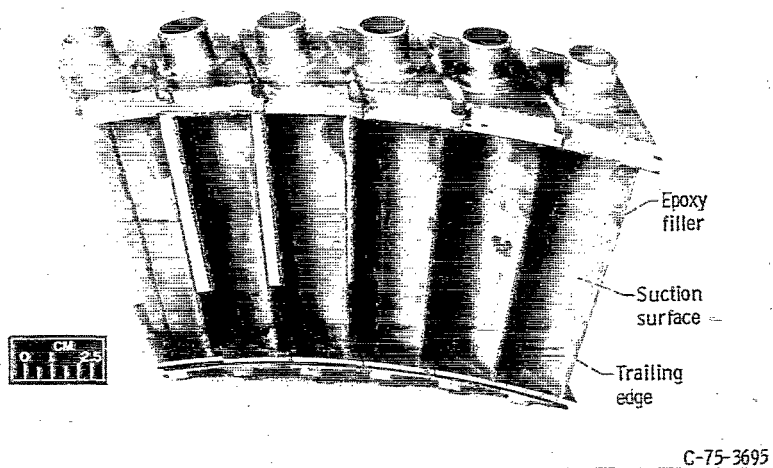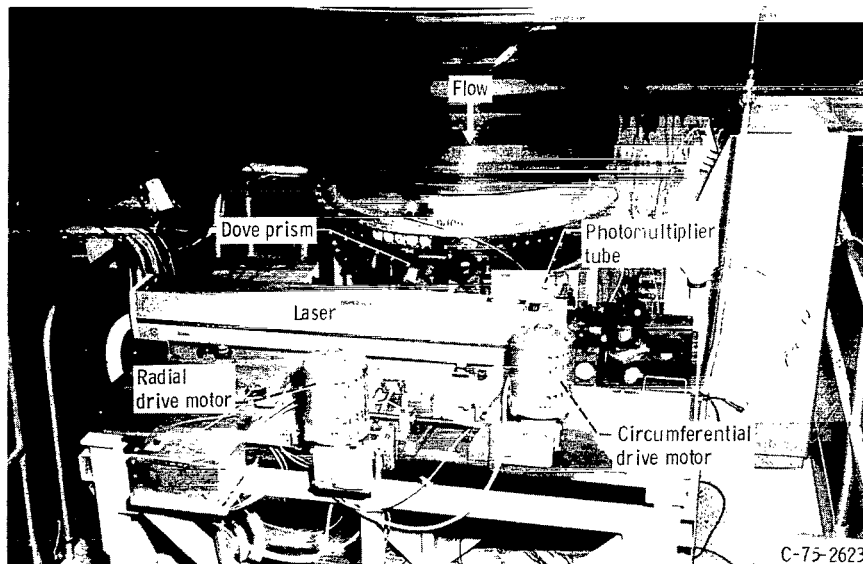

Figure 3. – Turbine stator vanes.
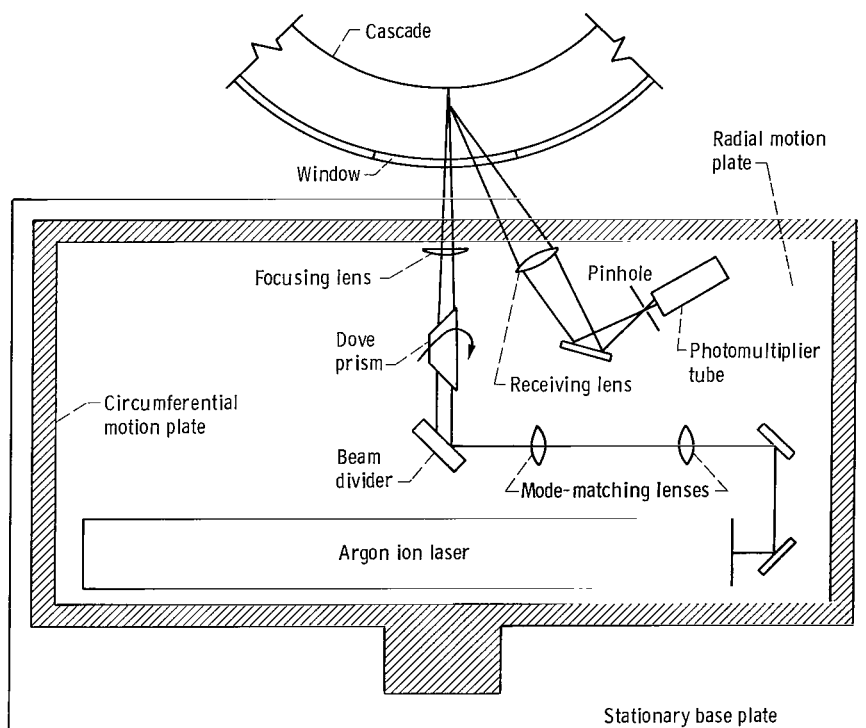
Figure 4. - Laser Doppler velocimeter.

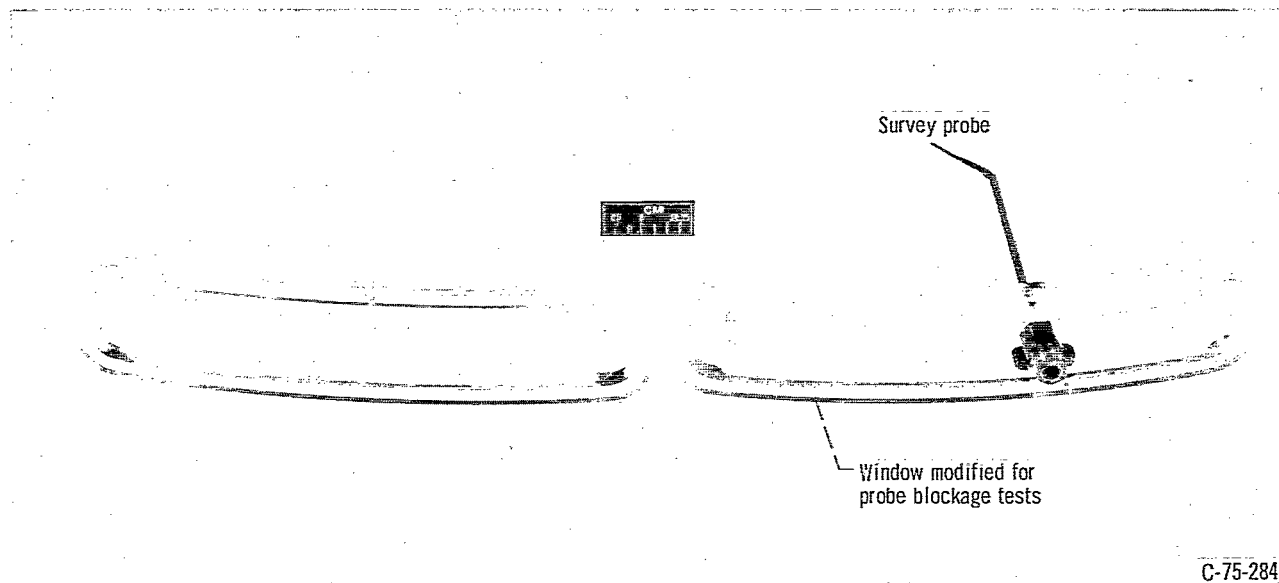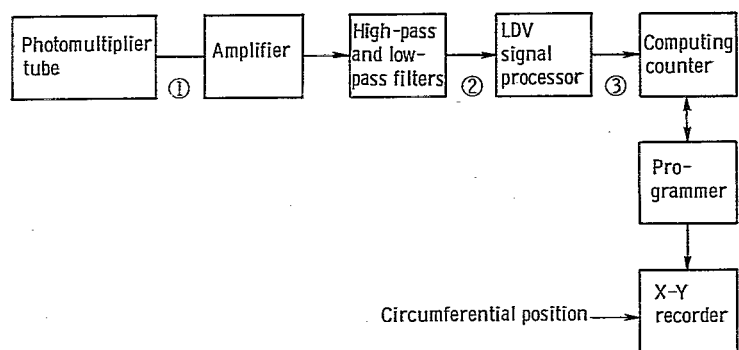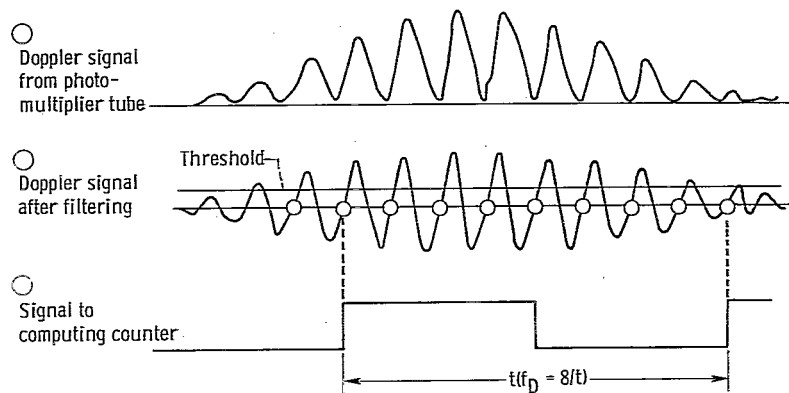Figure 5. - Schematic of laser Doppler velocimeter and traversing mechanism.

Figure 6. - Laser Doppler velocimeter windows.

(a) Block diagram of laser Doppler velocimeter electronics.
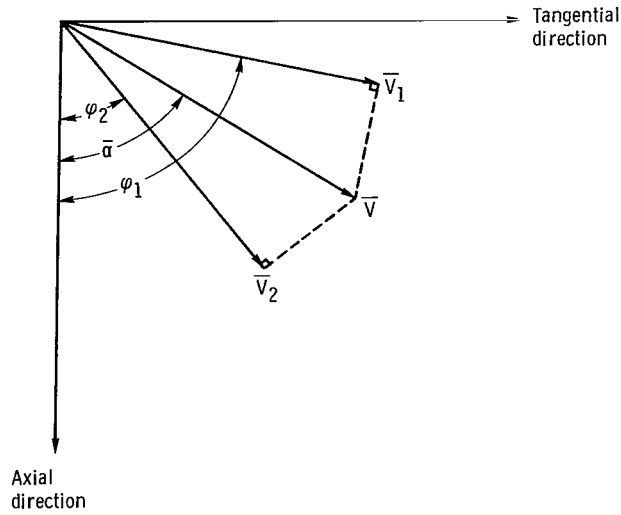

(b) Selected waveforms.

Figure 7. - Laser Doppler velocimeter electronics.

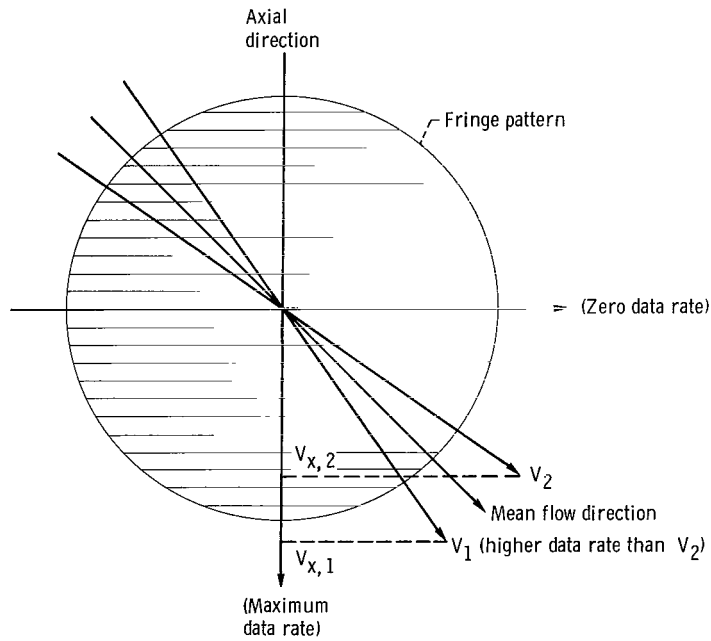Figure 8. – Nomenclature and orientation of velocity component measurements.

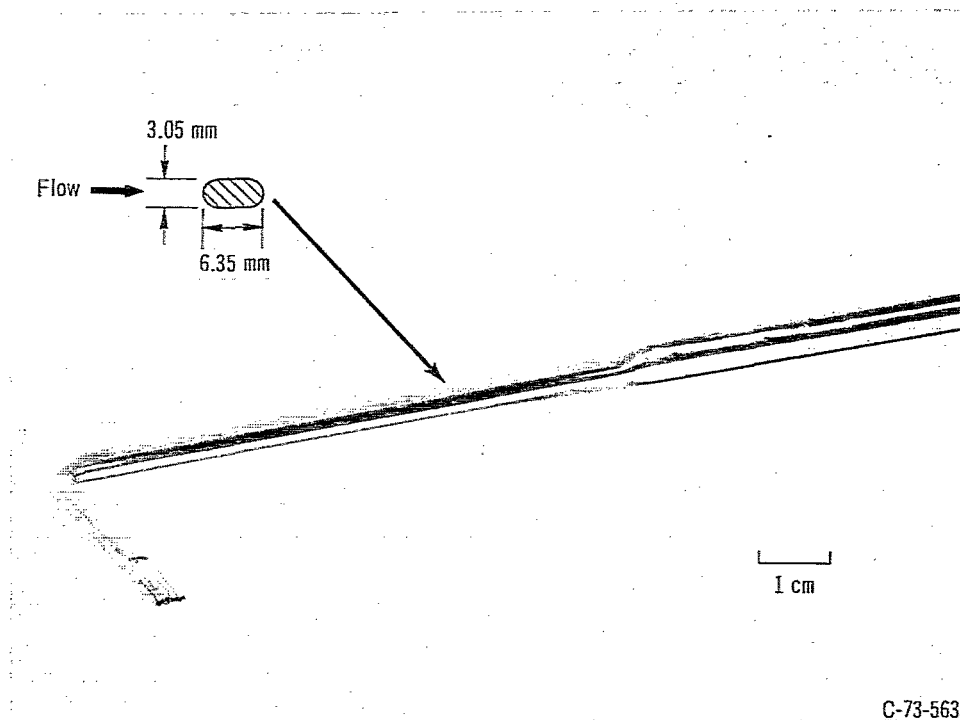Figure 9. – Angle biasing in velocity component measurements.

20

3.05 mm

Flow ⟶

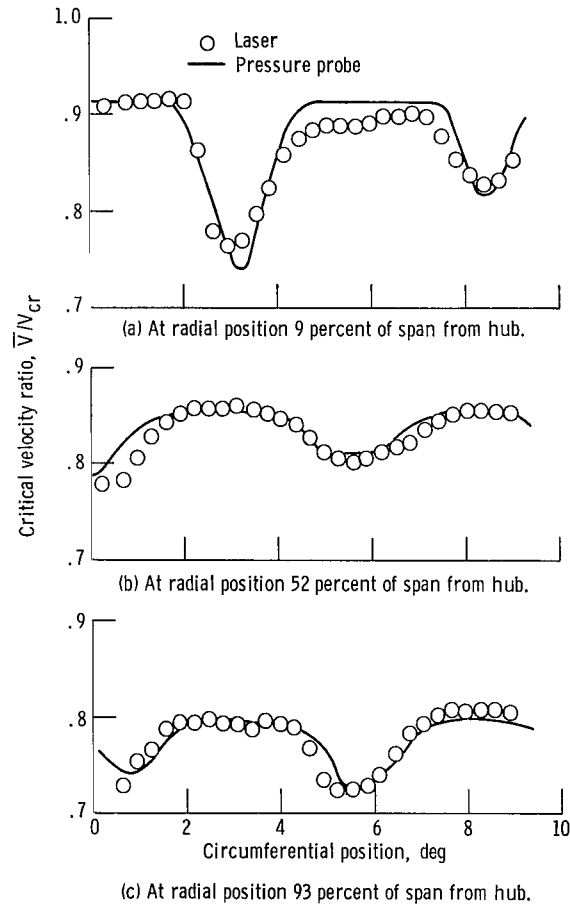6.35 mm

1 cm

C-73-563

Figure 10. - Survey probe.

(a) At radial position 9 percent of span from hub.

(b) At radial position 52 percent of span from hub.

(c) At radial position 93 percent of span from hub.

Figure 11. – Comparison of critical velocity ratios obtained from survey pressure probe and laser discrete point measurements.
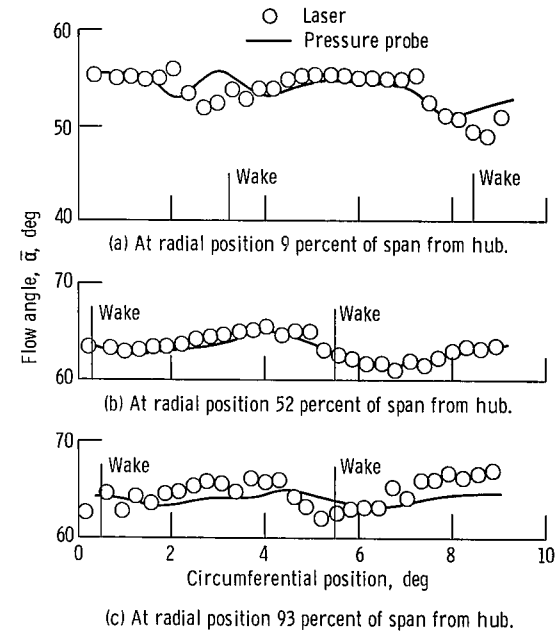
(a) At radial position 9 percent of span from hub.

(b) At radial position 52 percent of span from hub.

(c) At radial position 93 percent of span from hub.

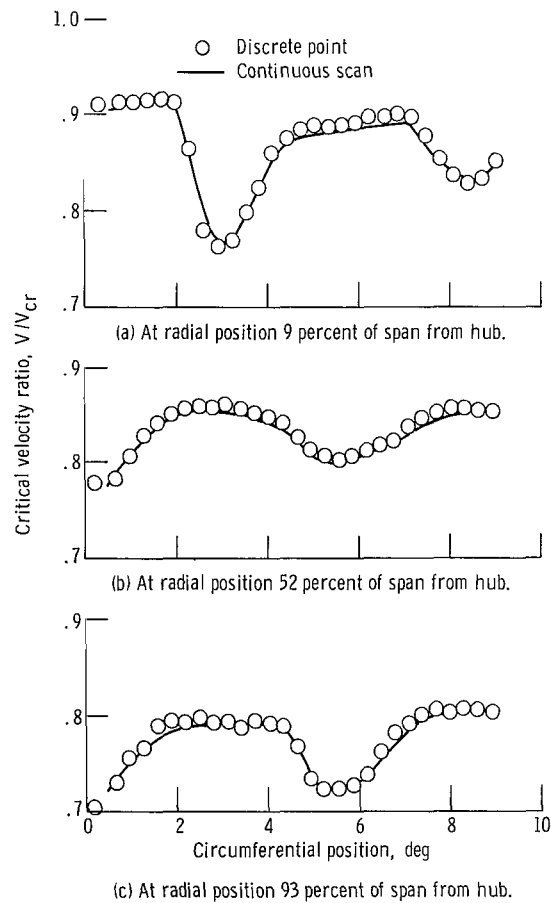Figure 12. – Comparison of flow angles obtained from survey pressure probe and laser discrete point measurements.

(a) At radial position 9 percent of span from hub.

(b) At radial position 52 percent of span from hub.

(c) At radial position 93 percent of span from hub.

Figure 13. – Comparison of two modes of obtaining laser survey measurements.

(a) At radial position 9 percent of span from hub.

(b) At radial position 52 percent of span from hub.

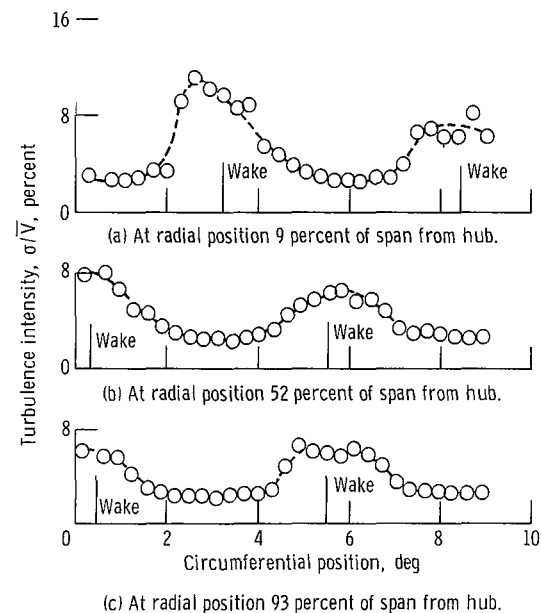(c) At radial position 93 percent of span from hub.

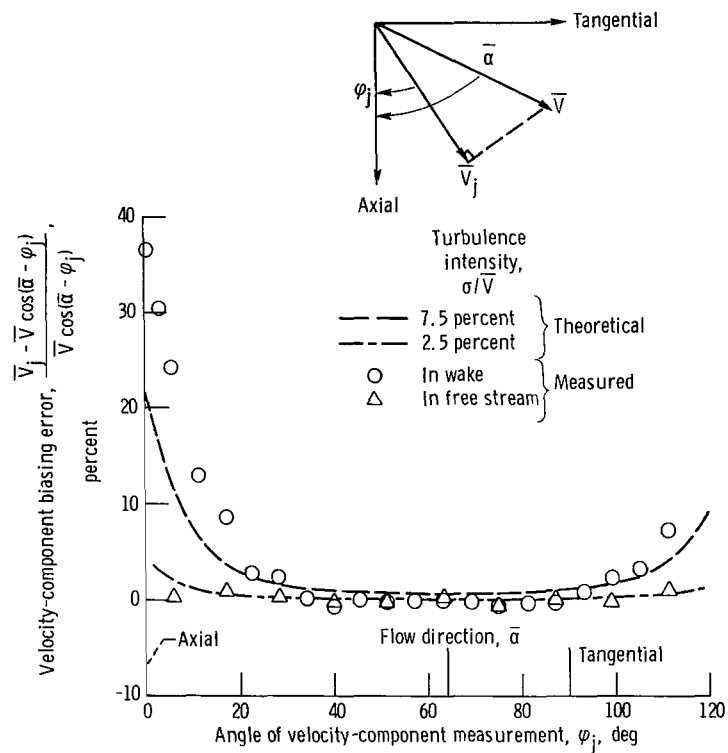Figure 14. – Variation of turbulence intensity with circumferential and radial position.

Figure 15. - Biasing of velocity measurements due to velocity fluc-
tuations at radial position 52 percent of span from hub.

(a) At radial position 9 percent of span from hub.

(b) At radial position 52 percent of span from hub.
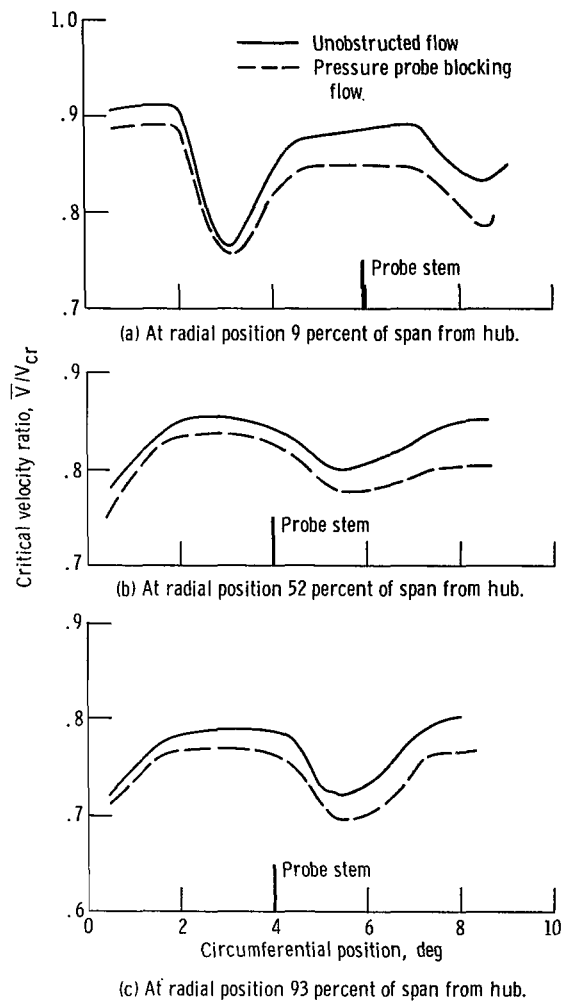
(c) At radial position 93 percent of span from hub.

Figure 16. - Effect of pressure probe blockage on critical
velocity ratio distribution at vane exit. (Probe at fixed
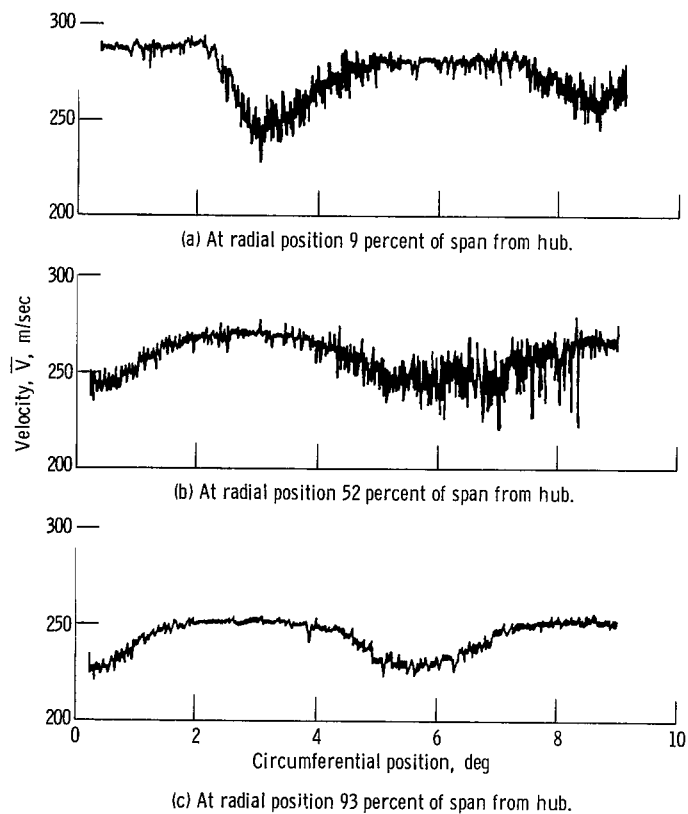radial position of 9 percent of span from hub.)

(a) At radial position 9 percent of span from hub.

(b) At radial position 52 percent of span from hub.

(c) At radial position 93 percent of span from hub.

Figure 17. - Continuous scan laser velocity surveys with condensation occurring in stator.

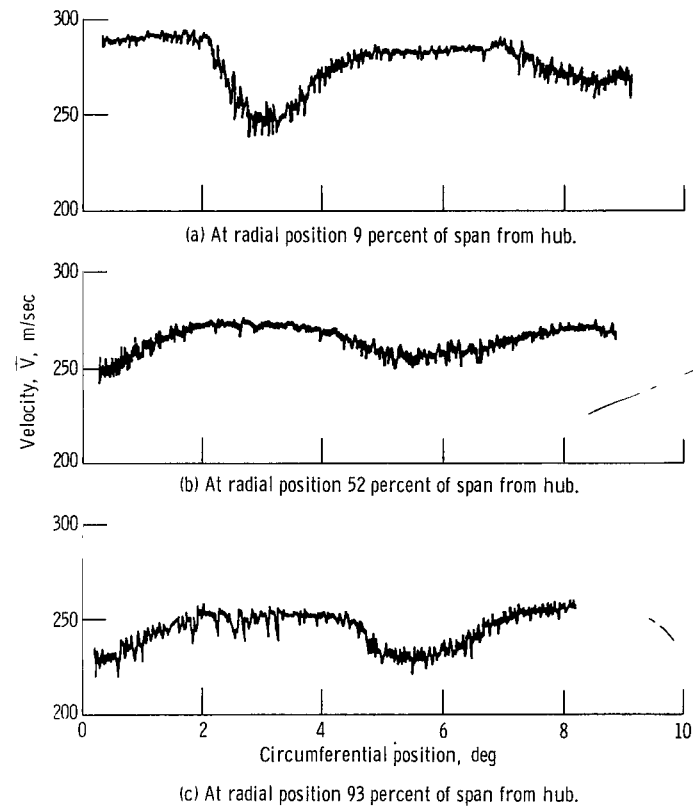(a) At radial position 9 percent of span from hub.

(b) At radial position 52 percent of span from hub.

(c) At radial position 93 percent of span from hub.

Figure 18. - Continuous scan laser velocity surveys without condensation occurring in stator.

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